

# Duality in Meson Electroproduction – Update

**Submitted by**      *(these are the people involved in last year's E00-108 run)*

R. Asaturyan, H. Mkrtchyan (spokesperson), T. Navasardyan, V. Tadevosyan  
*Yerevan Physics Institute, Armenia*

J. Beaufait, P. Bosted, R. Ent (spokesperson), H. C. Fenker, D. Gaskell, M. Jones,  
D. J. Mack, D. Meekins, A. F. Lung, J. Roche, G. Smith, W. F. Vulcan, G. Warren,  
S. A. Wood, C. Yan  
*Jefferson Laboratory, Newport News, VA*

G. Niculescu (spokesperson), I. Niculescu  
*James Madison University, Harrisonburg, VA*

J. R. Arrington, X. Zheng  
*Argonne National Laboratory, Argonne, IL*

J. Reinhold  
*Florida International University, Miami, FL*

O. K. Baker, M. E. Christy, W. Hinton, C. E. Keppel, S. Malace, E. Segbefia, L. Tang,  
A. Uzzle, L. Yuan  
*Hampton University, Hampton, VA*

T. Dodario, N. El Khayari, E. Hungerford, N. Kalantarians, Y. Li  
*Houston University, Houston, TX*

H. Breuer, T. Horn  
*University of Maryland, College Park, MD*

F. Wesselmann  
*Norfolk State University, Norfolk, VA*

Y. Liang  
*Ohio University, Athens, OH*

P. Stoler  
*Rensselaer Polytechnic Institute, Troy, NY*

X. Jiang  
*Rutgers University, Piscataway, NJ*

D. B. Day  
*University of Virginia, Charlottesville, VA*

M. Dalton, S. Connell  
*University of the Witwatersrand, Witwatersrand, South Africa*

# Abstract

Experiment E00-108, Duality in Meson Electroproduction, was approved by PAC-18 for 20 days. It was scheduled for 10 PAC-days of data taking in August 2003. The experiment explored the duality between quark and hadron descriptions in semi-inclusive electron scattering. In particular, E00-108 studied the meson (pion, and, with reduced statistics, kaon) electroproduction cross-section as a function of  $z$ , Bjorken  $x$ , and  $Q^2$ , from 4 cm LH2 and LD2 targets, and Al “dummy” targets. To allow simultaneous access to the  $(e,e'K^\pm)$  channels, the collaboration designed, constructed, and commissioned a new Aerogel detector for HMS that was successfully used in 2003.

The E00-018 experiment was proposed to use a 6 GeV electron beam to perform electron-meson coincidence measurements for  $Q^2$  between 1.8–6.0 GeV<sup>2</sup>,  $0.2 \leq x \leq 0.7$ , and  $z$  in the 0.45–0.85 range. In 2003, a 5.5 GeV electron beam energy was used to measure the complete  $z$ -range over a limited  $x$  range ( $\leq 0.55$ ). In addition, the time allocated only permitted a verification of the  $p_T$  dependence at one value of  $(x,z)$ . Here, we request the remaining 10 days, that fall in the jeopardy category, to be approved to extend the range in  $x$  and quantify the  $p_T$ -dependence over a larger of  $z$ . We note that the latter was one of the suggestions of an earlier PAC (see PAC17 Report).

## I. INTRODUCTION

Scaling is a well established phenomenon in deep inelastic scattering. The cross section is proportional to structure functions that depend only on the scaling variable  $x$ , up to calculable logarithmic  $Q^2$  corrections. Both the observation of scaling and subsequently the (logarithmic) scaling violations in the measured structure functions played a crucial role in establishing QCD as the accepted theory of strong interactions, and in mapping out the distributions of the constituents of protons and neutrons.

The observation of duality between the various inclusive structure functions measured in the resonance region and those in the deep inelastic limit further indicates that the single quark scattering process is still decisive in setting the scale of the reaction, even in the region dominated by nucleon resonances. Apparently, the role of final state interactions required to form the resonances becomes almost insignificant when averaged over the resonances.

While duality between inclusive electron-hadron scattering in the resonance and deep inelastic regimes is well established, the existence of a similar duality in *semi-inclusive* electron scattering,  $eN \rightarrow ehX$ , in which a hadron  $h$  is detected in the final state in coincidence with the scattered electron, has not yet been tested [1]. The virtue of semi-inclusive production in a partonic basis lies in the ability to identify individual quark species in the nucleon by tagging specific mesons in the final state, which enables both the flavor and spin of quarks and antiquarks to be systematically determined. At high energy, if a partonic description is applicable, the scattering and production mechanisms are independent, and the cross section is given by a simple product of quark distribution and a quark  $\rightarrow$  hadron fragmentation function,

$$\frac{d\sigma}{dx dz} \sim \sum_q e_q^2 q(x, Q^2) D_{q \rightarrow h}(z, Q^2) , \quad (1)$$

where the fragmentation function  $D_{q \rightarrow h}(z, Q^2)$  gives the probability for a quark to fragment into a hadron  $h$  with a fraction  $z$  of the quark (or virtual photon) energy,  $z = E_h/\nu$ . In the current fragmentation region the quark typically fragments into a meson  $m$ , which we shall focus on here. A central question for the applicability of a partonic interpretation of semi-inclusive DIS (1) is whether the probability to incoherently scatter from an individual parton, and the subsequent probability that the parton fragments into a particular meson, can be factorized. In other words, whether the  $x$  and  $z$  distributions factorize as in Eq. (1). While this is expected at high energies, it is not at all clear that this is the case at low energies, such as those available at HERMES or Jefferson Lab. In the original proposal to PAC-18 (attached) we reviewed the empirical status of semi-inclusive  $\pi$  production. Here, we complement this by first revisiting the issue of low-energy (or precocious) factorization and then discussing theoretical and phenomenological approaches to duality in semi-inclusive processes.

## II. LOW-ENERGY FACTORIZATION

At high energies, one expects from perturbative QCD that there will be factorization between the virtual photon–quark interaction and the subsequent quark hadronization, as in Eq. (1). A consequence of this factorization is that the fragmentation function is independent of  $x$ , and the quark distribution function is independent of  $z$ . Both the quark distribution functions and the fragmentation functions, however, depend on  $Q^2$  through logarithmic  $Q^2$  evolution.

The fragmentation functions parameterize how a quark involved in a high-energy scattering reaction evolves into the hadron that is detected. Initial investigations of the hadronization process were made in electron-positron annihilation and in deep inelastic scattering. In the latter case, high energies were used to separate the hadrons produced by the struck quark (current fragmentation) from those originating from the spectator quark system (target fragmentation), using large intervals in rapidity. The rapidity is defined in terms of the produced meson energy ( $E_m$ ) and longitudinal component of the momentum (along the  $\vec{q}$  direction,  $p_m^z$ ) as:

$$\eta = \frac{1}{2} \ln \left( \frac{E_m - p_m^z}{E_m + p_m^z} \right) . \quad (2)$$

Experience from CERN data [2,3] suggests that a rapidity gap of  $\Delta\eta \approx 2$  is needed to kinematically separate the two regions.

At lower energies, it is not obvious that the pion electroproduction process factorizes in the same manner as in Eq. (1). We will simply assume that factorization holds if one can reach a region where kinematical separation between current and target fragmentation is possible, and one is in the semi-inclusive equivalent of the “DIS” region. The latter we define for semi-inclusive reactions to be  $W'^2 > 4 \text{ GeV}^2$ , in analogy with the  $W^2 > 4 \text{ GeV}^2$  requirement for inclusive scattering.

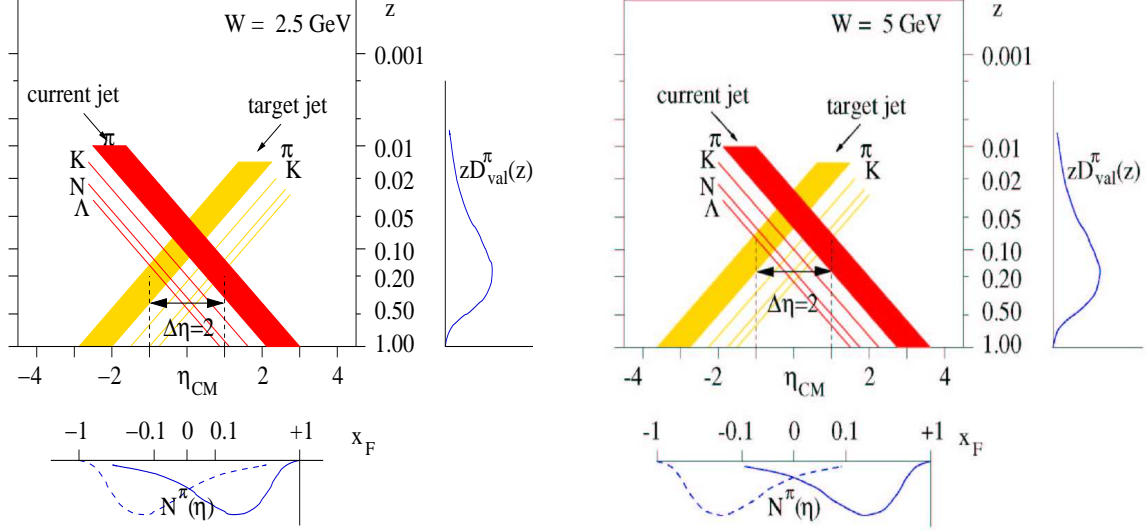


FIG. 1. Relation between elasticity  $z$  and center of mass rapidity  $\eta_{\text{CM}}$  in semi-inclusive fragmentation for  $W = 2.5$  GeV (left panel) and  $W = 5$  GeV (right panel). Corresponding distributions versus the variable  $x_F$  (or Feynman  $x$ ) are also shown below the main graphs. (Adapted from Ref. [4]).

It has been argued that it is possible to reach such kinematic separation, even at low  $W^2$ , if one considers only electroproduced mesons with large elasticity  $z$ , i.e., with energies close to the maximum energy transfer [4,3]. Figure 1 shows a plot of rapidity versus  $z$  for  $W = 2.5$  GeV and  $W = 5$  GeV, respectively. At  $W = 2.5$  GeV, a rapidity gap of  $\Delta\eta \geq 2$  would be obtained with  $z > 0.4$  for pion electroproduction. For larger  $W$ , such a rapidity gap could already be attained at a lower value of  $z$ . Hence, one would anticipate a reasonable separation between the current and target fragmentation processes for  $z > 0.4$  and  $z > 0.2$ , at  $W = 2.5$  and 5 GeV, respectively.

Data from the annihilation process  $e^+e^- \rightarrow hX$  [5,6] further show that beyond  $z \approx 0.5$  at  $W = 3$  GeV ( $W' = 1.94$  GeV) a fragmentation function may have developed. The region extends to  $z \geq 0.2$  for  $W = 4.8$  GeV ( $W' = 2.84$  GeV) and to  $z \geq 0.1$  for  $W = 7.4$  GeV ( $W' = 4.14$  GeV). For  $z > 0.3$ , fragmentation functions have also been obtained from data [7] on  $ep \rightarrow e'\pi^\pm X$  at an incident energy  $E = 11.5$  GeV, with  $3 < W < 4$  GeV. All of these data are beyond the nucleon resonance region as defined above.

At even lower energies, a series of measurements of semi-exclusive pion electroproduction was carried out at Cornell, with both hydrogen and deuterium targets [8–10], covering a region in  $Q^2$  between 1 and 4 (GeV/c)<sup>2</sup> and in  $\nu$  between 2.5 and 6 GeV. The data from these experiments were analyzed in terms of an invariant structure function (analogous to  $d\sigma/dx dz$  in Eq. (1)), written in terms of the sum of products of parton distribution functions and parton fragmentation functions. The authors conclude that within their region of kinematics this invariant structure function shows no  $Q^2$  dependence, and a weak  $W^2$  dependence. This is particularly striking if one realizes that the kinematics in these experiments covered a region in  $W^2$  between 4 and 10 GeV<sup>2</sup>, and in  $z$  between 0.1 and 1. In fact, for a portion of the kinematics one is in the region  $M_n^2 < W'^2 < 4$  GeV<sup>2</sup>, right within the nucleon resonance region. Nonetheless, the data surprisingly were found to exhibit hints of a scaling

behavior [11]. Even the dependence of the measured cross sections as a function of transverse momentum  $p_\perp$ , which was only low,  $< 0.5$  GeV, in these data, was found to scale. In the kinematics plot of Fig. 1 (left panel), one would anticipate factorization to work reasonably well for large  $z$ . Since the experimental data already show hardly resonance structure at  $W'^2 > 2$  GeV<sup>2</sup> (as for the Cornell data [8–10]), duality may follow simply from the fact that one cannot clearly distinguish the resonance and scaling regions, and from the existence of the factorization at large  $z$  [12,13].

### III. DYNAMICAL MODELS OF DUALITY IN PION PRODUCTION

In terms of hadronic variables the fragmentation process can be described through the excitation of nucleon resonances,  $N^*$ , and their subsequent decays into mesons and lower lying resonances, which we denote by  $N'^*$  [14]. The hadronic description must be rather elaborate, however, as the production of a fast outgoing meson in the current fragmentation region at high energy requires non-trivial cancellations of the angular distributions from various decay channels [15,12]. The duality between the quark and hadron descriptions of semi-inclusive meson production is illustrated in Fig. 2. Heuristically, this can be expressed as [12,16]

$$\sum_{N'^*} \left| \sum_{N^*} F_{\gamma^* N \rightarrow N^*}(Q^2, W^2) \mathcal{D}_{N^* \rightarrow N'^* m}(W^2, W'^2) \right|^2 = \sum_q e_q^2 q(x, Q^2) D_{q \rightarrow m}(z, Q^2), \quad (3)$$

where  $D_{q \rightarrow m}$  is the quark  $\rightarrow$  meson fragmentation function for a given fraction  $z$  of the quark (or virtual photon) energy carried by the meson,  $z = E_m/\nu$ ,  $F_{\gamma^* N \rightarrow N^*}$  is the  $\gamma^* N \rightarrow N^*$  transition form factor, which depends on the masses of the virtual photon and excited nucleon ( $W = M_{N^*}$ ), and  $\mathcal{D}_{N^* \rightarrow N'^* m}$  is a function representing the decay  $N^* \rightarrow N'^* m$ , where  $W'$  is the invariant mass of the final state  $N'^*$ .

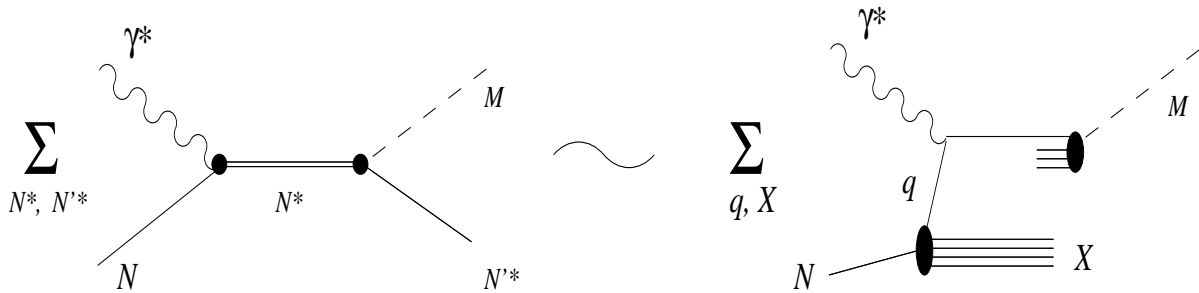


FIG. 2. Duality between descriptions of semi-inclusive meson production in terms of nucleon resonance (left) and quark (right) degrees of freedom [12,16].

The summations over hadronic states in Eq. (3) are considerably more involved theoretically than the corresponding sums in inclusive scattering. Nevertheless, there has been

work in models which has attempted to carry out the resonance sums explicitly. Close & Isgur [12] applied the SU(6) symmetric quark model to calculate production rates in various channels in semi-inclusive pion production,  $\gamma N \rightarrow \pi X$ . The pattern of constructive and destructive interference, which was a crucial feature of the appearance of duality in inclusive structure functions, is also repeated in semi-inclusive scattering. Defining the yields of photo-produced pions as

$$\mathcal{N}_N^\pi(x, z) = \sum_{N'^*} \left| \sum_{N^*} F_{\gamma N \rightarrow N^*}(W^2/Q^2) \mathcal{D}_{N^* \rightarrow N'^* \pi}(W'^2/Q^2) \right|^2, \quad (4)$$

the breakdown of  $\mathcal{N}_N^\pi$  into the individual states in the SU(6) supermultiplets for the final  $W'$  states is shown in Table I for both proton and neutron initial states.

$N'^*$ multiplet	$\gamma p \rightarrow \pi^+ N'^*$	$\gamma p \rightarrow \pi^- N'^*$	$\gamma n \rightarrow \pi^+ N'^*$	$\gamma n \rightarrow \pi^- N'^*$
$^2\mathbf{8}[\mathbf{56}^+]$	100	0	0	25
$^4\mathbf{10}[\mathbf{56}^+]$	32	24	96	8
$^2\mathbf{8}[\mathbf{70}^-]$	64	0	0	16
$^4\mathbf{8}[\mathbf{70}^-]$	16	0	0	4
$^4\mathbf{10}[\mathbf{70}^-]$	4	3	12	1
total $\mathcal{N}_N^\pi$	216	27	108	54

TABLE I. Relative strengths of SU(6) multiplet contributions to inclusive  $\pi^\pm$  photoproduction off the proton and neutron [12].

A comparison of the results of the hadronic sums with the quark level calculation, Eq. (1), can be made by considering the single quark fragmentation limit, in which  $z \approx 1$ . Here the scattered quark has a large probability of emerging in the observed pion, and the hadronization process is dominated by a single (leading) fragmentation function. For  $u$  quarks, for instance, the fragmentation into  $\pi^+$  at large  $z$  dominates than into  $\pi^-$ , so that  $D_u^{\pi^-}/D_u^{\pi^+} \rightarrow 0$  as  $z \rightarrow 1$ . Isospin symmetry also implies that  $D_d^{\pi^-} = D_u^{\pi^+}$ . This limit allows ratios of production rates to be computed directly in terms of ratios of quark distributions. For the case of SU(6) symmetry, where the quark distributions are simply related by  $u = 2d$ , one finds that both the relative yields of  $\pi^\pm$  mesons off, and the ratio of  $\pi^+$  to  $\pi^-$  yields for, protons and neutrons coincide exactly with those obtained from summations over coherent states in the  $\mathbf{56}^+$  and  $\mathbf{70}^-$  multiplets! This suggests that both factorization and duality arise if one sums over all the states in the lowest-lying even and odd parity multiplets. Furthermore, one also sees that at large  $Q^2$  and  $W^2$  approximate duality may be obtained by including just the  $\mathbf{56}^+$  multiplet and the  $^2\mathbf{8}[\mathbf{70}^-]$  states, which phenomenologically corresponds to integrating over  $W'$  up to  $\sim 1.7$  GeV. For the  $\mathcal{N}_p^{\pi^-}$  and  $\mathcal{N}_n^{\pi^+}$  channels, duality is saturated to  $\approx 90\%$  already by the nucleon elastic and  $\Delta$  states alone. One may therefore expect factorization and approximate duality at  $W'^2 \leq 3$  GeV<sup>2</sup>.

#### IV. KINEMATICS

The original E00-108 proposal was approved for 20 days of beam time at a beam energy of 6 GeV. The goal of the experiment was to study quark-hadron duality and factorization in semi-inclusive meson electroproduction. The cross sections for  $ep \rightarrow e\pi^+ + W'$ ,  $ep \rightarrow e\pi^- + W'$ ,  $ed \rightarrow e\pi^+ + W'$ , and  $ed \rightarrow e\pi^- + W'$  were to be measured as function of  $x$ ,  $z$ , and missing mass  $W'$  of the remaining hadronic system. Direct comparisons of these cross sections has intrinsic interest and could be used to test duality in these processes, whether or not factorization holds. Conversely, the data could also be used to test factorization, which, if found to hold, would open up new lines of investigation into quark fragmentation and QCD at 6-GeV kinematics.

$\theta_e$ deg.	$E'$ GeV	$\nu$ GeV	$Q^2$ (GeV/c) <sup>2</sup>	$x$	$W^2$ GeV <sup>2</sup>	$ \vec{q}_{\gamma^*} $ GeV/c	$\theta_{\gamma^*}$ deg.	$\theta_m$ deg.	$z$	$p_m$ GeV/c	$W'^2$ GeV <sup>2</sup>
28.71	1.702	3.794	2.30	0.32	5.70	4.09	11.54	11.54	0.37	1.397	3.92
									0.42	1.606	3.65
									0.49	1.846	3.35
									0.55	2.122	3.00
									0.64	2.439	2.60
									0.74	2.803	2.13
									0.85	3.222	1.60
									0.97	3.703	1.00
28.71	1.702	3.794	2.30	0.32	5.70	4.09	11.54	11.54	0.55	2.082	3.05
31.75			2.80	0.39	5.20	4.15	12.47	12.47			2.82
34.55			3.30	0.46	4.70	4.21	13.27	13.27			2.60
37.17			3.80	0.53	4.20	4.27	13.95	13.95			2.37
28.71	1.702	3.794	2.30	0.32	5.70	4.09	11.54	13.54	0.55	2.082	3.05
								15.54		2.150	3.22
								19.54			
28.0	1.30	4.00	1.61	0.21	6.77	4.20	8.96	10.5	0.50	2.00	3.83
45.0	1.40	3.90	4.35	0.59	3.85	4.42	18.50			1.95	2.37
54.0	1.20	4.10	5.24	0.68	3.33	4.70	16.21			2.05	2.10
29.48	1.67	4.33	2.60	0.32	6.40	4.62	10.27	10.27	0.55	2.37	3.36
								15.5	0.35	1.51	4.47
								15.5	0.45	1.95	3.92
								15.5	0.65	2.81	2.81
								15.5	0.75	3.24	2.26
								15.5	0.85	3.68	1.71
								15.5	0.95	4.11	1.16

TABLE II. *Top*: Kinematics measured in the August, 2003 part of the E00-108 experiment, at a beam energy of 5.5 GeV. *Bottom*: Kinematics to be measured to extend the  $x$  range of the E00-108 experiment, and verify the  $p_T$  dependence, at a beam energy of 6 GeV.

To allow for a meaningful comparison of quark-gluon and hadronic descriptions, the PAC recommended to ensure a comparable  $p_T$  range at various kinematics. This recommendation reflects the consideration that at small  $W'$  any  $p_T$  dependence may be due to the angular decay pattern of few resonances only, where at large  $W'$  the  $p_T$ -dependence consistent with high-energy processes should emerge. For this reason, the E00-108 proposal had additional measurements for  $\Theta_{HMS} = \Theta_q + 5^\circ$  at each kinematics.

In 2003, we executed half of the E00-108 experiment at a beam energy of 5.5 GeV. In short, we measured the  $z$ -dependence at fixed  $x = 0.32$ , and the  $x$ -dependence at fixed  $z = 0.55$ . In the latter, we did not extend to  $x > 0.55$  as the high- $x$  kinematics would have taken an appreciable amount of beam time. We did do an extensive  $p_T$  scan at  $(x = 0.32, z = 0.55)$ .

In most of the kinematics we kept the meson momentum in the final state,  $p_m$ , larger than 2 GeV to avoid complications from  $\pi$ -N final state interactions. However, we did add some high count rate kinematics at lower  $p_m$  to push to lower  $z$ . The kinematics of the August, 2003, part of E00-108 are listed in Table II.

The kinematics in the bottom part of Table II are those for which we request beam time in this Update proposal. Here, we assumed a beam energy of 6 GeV. To complete this portion of the proposal we request the remaining 10 days of the E00-108 proposal. For count rate and beam time estimates we refer to the original E00-108 proposal.

In short, these remaining 10 days would allow us to

- Extend the  $x$  range at fixed  $z$  to 0.70.
- Measure the  $p_T$  dependence in the region of low  $W'$  (or large  $z$ ).

## V. PRELIMINARY RESULTS OF AUGUST 2003 RUN

*Note: since the initial 10 days of the E00-108 experiment data taking were scheduled only recently, starting mid-August 2003, we will only show preliminary results of the first-pass data analysis. This implies, e.g., that no corrections for variations in  $Q^2$  have been included yet, or that data from the “neutron” are at present simply obtained by subtracting proton from deuterium data. We expect to have final data by late Summer.*

We have added the possibility of semi-inclusive  $(e, e' m)$  ( $m = \pi, K$ ) electroproduction to the general Hall C Monte Carlo package SIMC [17], following the high-energy expectation of Eqn. 1. We used the CTEQ5 NLO parton distribution functions to parameterize  $q(x, Q^2)$ , and the fragmentation function parameterization for  $D_{q \rightarrow m}^+(z, Q^2) + D_{q \rightarrow m}^-(z, Q^2)$ , with  $D^+$  ( $D^-$ ) the favored (unfavored) fragmentation function, from Binnewies *et al.* [18]. The remaining unknowns, the ratio of  $D^-/D^+$  [19] and the slope  $b$  [20] of the  $p_T$  dependence (see Eqn. 3 of the original E00-108 proposal) are taken from HERMES analyses.

The results of the preliminary  $^1\text{H}(e, e' \pi^-)X$  cross section at  $x = 0.32$  are compared with the results of the simulation in Fig. 3, as a function of  $z$ . The general agreement between data and Monte Carlo is excellent, apart from at large  $z$  ( $> 0.7$ ).

To illustrate better what the origin of the discrepancy at large  $z$  is, we show the ratio of  $\pi^+/\pi^-$  cross sections for both proton and “neutron” targets as a function of  $W'$  (top) and  $z$

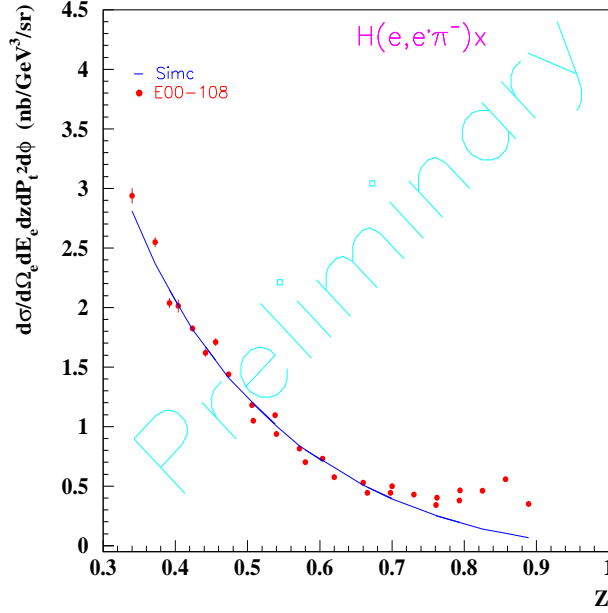


FIG. 3. The  $^1\text{H}(e,e'\pi^-)X$  cross section at  $x = 0.32$  as a function of  $z$  (solid circles) in comparison with a Monte Carlo simulation (solid curve) starting from a fragmentation ansatz (see text). The scatter of the data is due to having performed only a rudimentary bin centering, but is well within the present estimated uncertainties of 10-20%.

(bottom) in Fig. 4, again at  $x = 0.32$ . In such ratios one is less sensitive to global normalization problems (like absolute charge measurements or acceptance effects) and bin-centering effects. One can understand the discrepancy between  $^1\text{H}(e,e'\pi^-)$  data and a simulation assuming meson fragmentation by realizing that the  $z > 0.7$  region equals the  $W' < 1.6$  GeV region (as  $W'^2 = M^2 + Q^2(1/x - 1)(1 - z)$ ). The large “rise” in  $^1\text{H}(e,e'\pi^-)$  data with respect to the simulation in Fig. 3 at  $z > 0.7$  simply reflects the  $^1\text{H}(e,e'\pi^-)\Delta$  region. Indeed, if one considers a  $^1\text{H}(e,e'\pi^-)X$  spectrum as function of missing mass of the residual system  $X$ , one only sees one prominent resonance region, the  $\Delta$  region. Apparently, above  $W' = 1.6$  GeV there are already sufficient resonances in the missing mass spectrum of  $^1\text{H}(e,e'\pi^\pm)X$  that the  $\pi^+/\pi^-$  ratios are nearly flat as a function of  $W'$  or, equivalently,  $z$ , and one gets “apparent” factorization in  $x$  and  $z$ .

We can, as we did in the E00-108 proposal with a data sample from a Hall C test run in 1999, also determine ratios of  $D^-/D^+$  and  $d_v/u_v$ . For the former, we only use the  $^2\text{H}(e,e'\pi^\pm)X$  data, while for the latter we also need the  $^1\text{H}(e,e'\pi^\pm)X$  data. Either analysis is more sensitive to the uncertainties inherent in the preliminary state of the analysis. A 20% uncertainty in the ratio of  $\pi^+$  to  $\pi^-$  yields about a 40% uncertainty in the  $D^-/D^+$  ratio. Similarly, since the determination of the  $d_v/u_v$  ratio involves a difference of yields, here the uncertainty also is magnified with respect to the 10-20% estimate of uncertainties in the preliminary cross sections. Nonetheless, it is interesting to verify any *dependence* of  $D^-/D^+$  to  $x$  and of  $d_v/u_v$  to  $z$ . The preliminary results are shown in Fig. 5, where the top plot shows  $D^-/D^+$  as a function of  $x$ , at  $z = 0.55$ , and the bottom plot shows  $d_v/u_v$  as

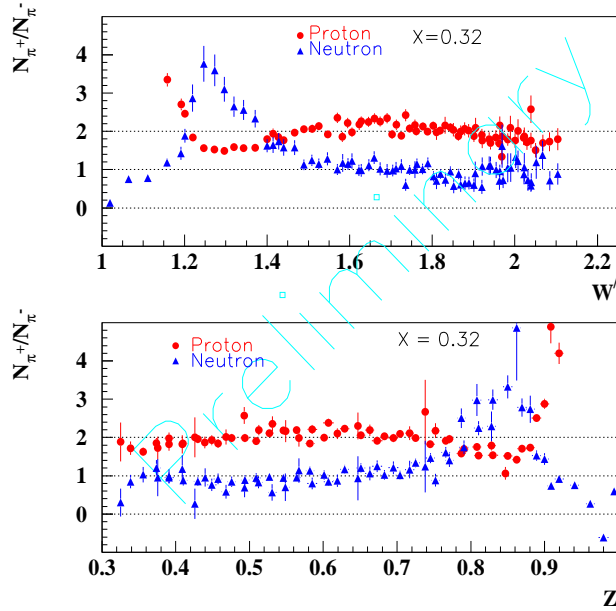


FIG. 4. The ratio of  $\pi^+$  to  $\pi^-$  yields of proton and “neutron” targets as a function of  $W'$  (top) and  $z$  (bottom), at  $x = 0.32$ .

a function of  $z$ , at  $x = 0.32$ . The lines show the approximate values as determined from high energy experiments. As one can see from Fig. 5, the ratio of  $D^-/D^+$  is reasonably independent of  $x$ , and the ratio of  $d_v/u_v$  is nearly independent of  $z$  up to  $z = 0.7$ . Although the actual values appear either larger (for  $D^-/D^+$ ) or smaller (for  $d_v/u_v$ ) than the high energy expectations, they are not inconsistent with the uncertainties of the present analysis.

Lastly, we compare in Fig. 6 the  $p_T$  dependence of  $^2\text{H}(e,e'\pi^+)X$  and  $^{27}\text{Al}(e,e'\pi^+)X$  with that of  $^1\text{H}(e,e'\pi^+)X$ , at  $(x,z) = (0.32,0.55)$ . The  $W'$  value at this  $(x,z)$  setting is approximately 1.8 GeV, well beyond the resonance region enhancements visually observed in an  $(e,e'\pi)$  spectrum at  $Q^2 > 0.5$  (GeV/c) $^2$ . The lines in Fig. 6 are fits to the data. The preliminary conclusion is that, at least at these  $(x,z)$  values, the  $p_T$  dependence is independent of target nucleus. However, the  $p_T$  dependence found in our preliminary analysis is slightly ( $\sim 20\%$ ) shallower than the  $p_T$  dependence found by the HERMES analysis [20] (not shown in Fig. 6).

As mentioned, one would expect the  $p_T$  dependence to change at smaller  $W'$ . Here, only a few resonance transitions contribute, such that the near-cancellations of angular decay patterns required to produce duality and a  $p_T$  dependence mimicking high energy data is not possible. Hence, we believe it of fundamental importance to experimentally measure the  $p_T$  dependence at several values of  $W'$  (or  $z$ ).

Summarizing, the preliminary results of the E00-108 experiment suggest the existence of quark-hadron duality in the semi-inclusive meson electroproduction process, and illustrate the origin of the onset of low-energy or precocious factorization. At least approximate duality and factorization seems to be valid for kinematics accessible at a 6-GeV Jefferson Lab. Of course, a quantification of these observations will need to wait for the final data analysis,

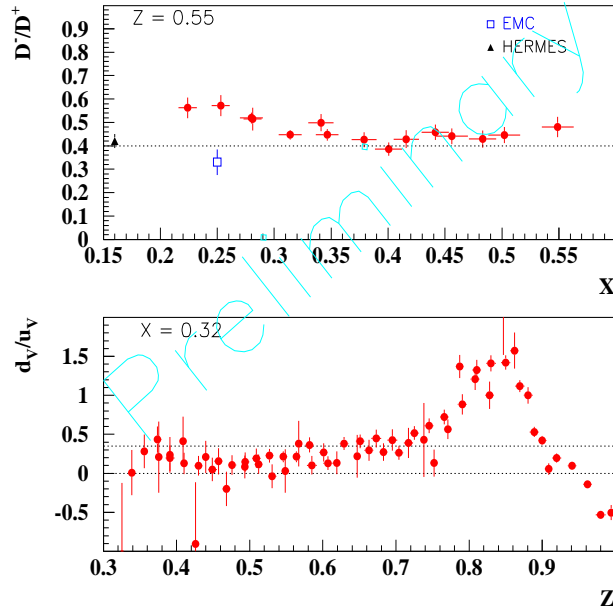


FIG. 5. *Top*: The ratio of unfavored to favored fragmentation function  $D^-/D^+$  (at  $z = 0.55$ ) as a function of  $x$ , using only deuterium data. *Bottom*: The ratio of valence down to valence up parton distribution functions  $d_v/u_v$  as a function of  $z$ , at  $x = 0.32$ . To extract a  $d_v/u_v$  ratio both hydrogen and deuterium data were used.

but the preliminary results obtained to date are encouraging.

## VI. THE HMS AEROGEL DETECTOR

For particle identification (PID) in the HMS spectrometer a combination of Time-of-Flight (TOF), a threshold gas Cherenkov counter and a segmented lead-glass electromagnetic calorimeter (EC) is used. In addition, for coincidence measurements, one uses the coincidence time difference between scattered electrons and secondary hadrons.

Nonetheless, the  $\pi/K/p$  separation dramatically deteriorates with momentum as  $\Delta t \sim 1/P^2$ . While TOF is very effective at low momentum, it becomes in practice useless above  $P \sim 3 \text{ GeV}/c$ . In addition, in this range hadrons tend to become above the detection threshold in gas Cherenkov detectors, making  $\pi/K/p$  separation more difficult. Thus, the HMS PID system needed to be augmented for good hadron identification above  $3 \text{ GeV}/c$ .

The E00-108 collaboration designed, built and commissioned a new Aerogel detector with two types of aerogel material:  $n = 1.03$  and  $n = 1.015$ . The detector consists of a tray with aerogel material followed by a light diffusion box. The radiator tray can easily be swapped for an alternate one with aerogel material with different index of refraction. This was in practice done in 2003, where the  $n = 1.03$  tray was requested by the E01-004 “Charged Pion Form Factor Extension” (the E00-108 experiment itself required the  $n = 1.015$  aerogel material).

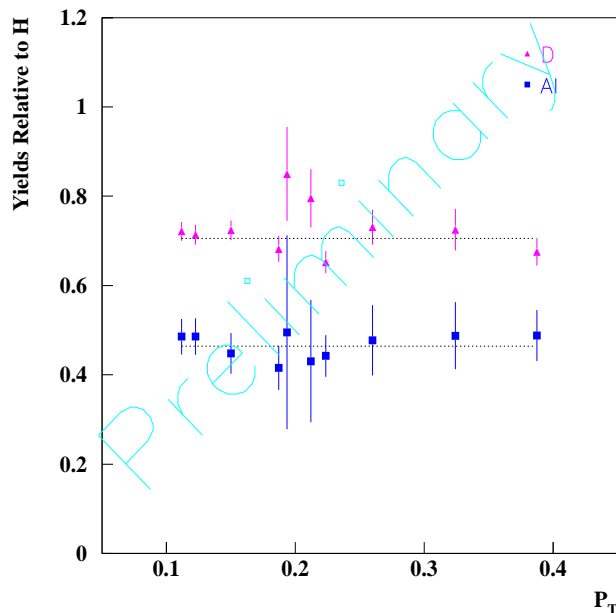


FIG. 6. The ratio of  $A(e,e'\pi^+)X$  ( $A = {}^2\text{H}, \text{Al}$ ) over  ${}^1\text{H}(e,e'\pi^+)X$  yields as a function of  $p_T$ .

The addition of this detector enhanced the capabilities of the spectrometer in distinguishing protons from pions on the level of  $2.8 - 1.1 \cdot 10^{-3}$  (for aerogel with  $n=1.03$ ) with a pion detection efficiency better than 99% in the 1-4 GeV/c momentum range.

The detector response shows no significant position dependence due to the diffuse light collection technique. The diffusion box was equipped with 16 Photonis XP4572 PMT's.

The mean numbers of detected photo-electrons are  $\sim 16$  and  $\sim 8$  for the  $n=1.030$  and  $n=1.015$  aerogel material, respectively. The detector response is uniform to within  $\sim 10\%$  over the full effective area. Moderate particle identification is feasible near threshold. The experimental results are in good agreement with expected values from Monte Carlo simulations. The detector is now part of the standard package for HMS, and is easily installed or removed.

## VII. BEAM TIME REQUEST

We request the remaining 10 days of the E00-108 experiment to be approved. The main physics thrusts of this part of the experiment is to access  $d_v/u_v$  at large  $x$  and to probe the  $p_T$  dependence (at varying values of  $W'$  and  $z$ ), in accordance with the suggestion of PAC-17 [21].

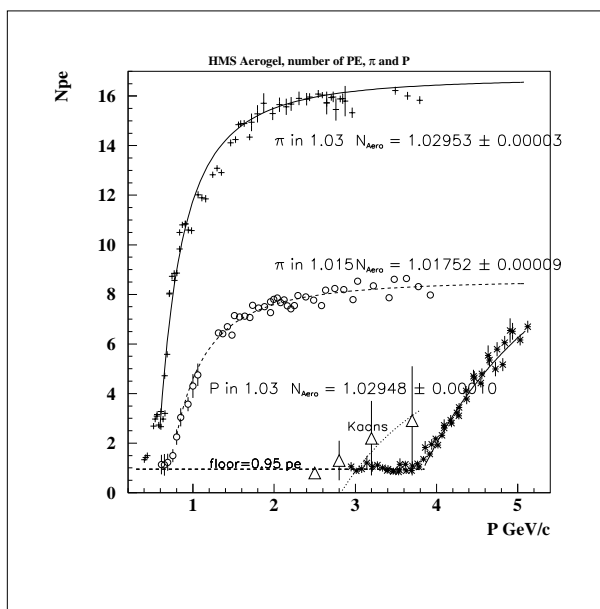


FIG. 7. The momentum dependence of the number of photo-electrons  $N_{pe}$  for both types of aerogel material used in 2003, and for different particles. Both the experimental results and the results of a fit are shown.

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